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# Forest Health Monitoring and Forest Inventory Analysis Programs Monitor Climate Change Effects in Forest Ecosystems

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**ABSTRACT**

The Forest Health Monitoring (FHM) and Forest Inventory and Analyses (FIA) programs are integrated biological monitoring systems that use nationally standardized methods to evaluate and report on the health and sustainability of forest ecosystems in the United States. Many of the anticipated changes in forest ecosystems from climate change were also issues addressed in sections of FHM's National Technical Report 1991 to 1998. The integrated FHM and FIA monitoring systems are currently establishing baseline conditions (status and change) in most States for many of the expected effects, and are projected to have full implementation for all States and 'Territories in 2003. These monitoring systems utilize a broad suite of indicators of key ecosystem components and processes that are responsive to many biotic and abiotic stressors, including those anticipated frorn climate change. These programs will contribute essential information for many decades for many of the anticipated changes in forest ecosystem from increasing carbon dioxide concentrations, changing climatic scenarios, and extreme weather events that are probable in the next 30 lo 100 yea-s.

**Key Words:** Forest Health Monitoring, Forest Inventory and Analyses, climate change, indicators, forest sustainability.

## INTRODUCTION

The Forest Health Monitoring (FHM) and Forest Inventory and Analyses (FIA) programs are integrated biological monitoring systems that annually evaluate, using

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nationally standardized methods, and report on the health and sustainability of forest ecosystems in the United States. Many of' the anticipated changes in forest ecosystems from climate change were also issues addressed in sections of FHM's National Technical Report 1991 to 1998. These monitoring systems utilize a broad suite of' indicators of key ecosystem components and processes that art: responsive to many biotic and abiotic stressors, including those anticipated from climate change. These programs will contribute essential information for many decades for many of the anticipated changes in forest ecosystem from increasing carbon dioxide concentrations, changing climatic scenarios, and extreme weather events that arc probable in the next 30 to 100 years.

The integrated FHM and FIA monitoring systems are currently establishing baseline conditions (status and change) in most States for many of the expected effects, and are projected to have full implementation for all States and Territories in 2003. These integrated monitoring systems have produced information on land-use patterns and forest fragmentation; tree growth, mortality, and diversity; insect and disease defoliation and mortality, and altered tree susceptibility to these agents; damage to trees from insects, diseases, storms, and other events; crown dieback and foliage transparency; exotic insects, pathogens, and plant species; fuel loading and alteration of' historic fire regimes; deviation in number of years of' moderate-to-severe drought; deposition of ozone and ion air pollutants; ozone injury on bioindicator species; soil nutrients, cotnpaction, and erosion; native, exotic, and lichen species richness; and tree and soil carbon.

The most common problems evaluated to date were (1) Related to direct human interaction with forest ecosystems such as forest fragmentation and land-use patterns; alteration of historic fire regimes; native insect and disease outbreaks and susceptibility of forests to these agents; and others; (2) related to the inadvertent introduction of a variety of relatively new biotic and abiotic stressors including ittvasivc insects, pathogens, and plant species; deposition of' toxic ions, low precipitation pH, and ozone; and others; and (3) a diverse group of indicator-s not yet specifically linked to causal agents including low soil pH and cations, deteriorating crown dieback and transparency, and relatively high mortality volume/live volume ratios, and deviations from historic averages in the number of moderate-to-severe drought years.

Climatic change is occurring globally and expected to accelerate sometime in tht next 30 to 100 years. 111 the near future it is expected to cause additional increases in $CO_2$ and other gases, increased temperatures, sea level rise, changes in patterns of precipitation and temperature, and changes in the frequency and severity of extreme weather events (USEPA 2000; NAST 2000a,b; IPCC 2001). These wide-spread climate changes are expected lo cause changes in forest productivity, increased insect and pathogen outbreaks, reduction of species richness due to reduced migration rates in fragmented forests, and disruption of key ecological relationships (Or-ions 1993). Some key strategies suggested to identify the impacts of climate change on resources include the classification of reliable sensitive indicators and development of extensive monitoring systems of biological diversity, community composition, and landscape metrics at local and regional scales (Kingsolver *et* al. 1993). These strategies arc met by the FHM and FIA monitoring programs.

This paper lists, with intended limited discussion, many of the expected climate change effects on forest ecosystems. The purpose is to compare anticipated climate change effects on forest ecosystems with the indicators currently in use in two national monitoring systems, the U.S. Forest Service's FHM program (Stolte 1997) and the FIA program (McRoberts *et al.* 2000). It is not intended to be a review of anticipated impacts (*e.g.*, Iverson and Prasad 1998; NAST 2000c), a thorough discussion of the severity and probable locations of impacts, or what analytical approaches will be used to delineate the impacts of climate change.

These programs have developed and implemented nationally standardized, long-term biological monitoring systems to detect changes in forest ecosystems from a wide variety of stressors, using attributes (indicators) of key ecological processes that are often disturbed when conditions change, such as changes in productivity, species diversity, *etc.* (Rapport *et al.* 1985). These monitoring programs were designed to track both short and long-term changes caused by a variety of biotic and abiotic factors, and utilize a broad suite of indicators that will also evaluate the effects of climate change (Stolte *et al.* 2001). Consequently, baseline conditions for many climate change indicators are being developed that will be useful for many decades.

The condition of forest ecosystems today is the result of the influences of three sets of factors. The first set is natural modifiers of forest ecosystems that include temperature, precipitation, fire, climate, geology, topography, insects and diseases (pathogens), and extreme weather events that have shaped forest ecosystems for millions of years. The second set is direct management activities that include timber harvest, fire suppression, and urban expansion. The third set is an ever-increasing number and type of new forest stressors that include air pollution, exotic species of many taxa, climate change, *etc.* These three sets of factors have combined in a multitude of ways to shape the boreal, temperate, subtropical, and tropical forests found in the U.S. today. As climate change accelerates, the distribution of major forest types and associated species will change in response to and follow the changing climate and weather patterns (NAST 2000c). In some cases the rate of climate change may exceed that rate at which forests can easily adjust and migrate (USEPA 2000; NAST 2000a; IPCC 2001)

## FOREST ECOSYSTEMS AND CLIMATE CHANGE IN THE U.S.

Forest ecosystems in the U.S. comprise 13% of the world's temperate forests and nearly a half of the coastal temperate rainforest in the world (USEPA 2000) About half of the U.S. forests are in private ownership. In the U.S. the northern expansion of temperate hardwoods and softwoods (deciduous and conifer species) are stopped from expanding northward by climatic factors (cold temperature sensitivity), and other climatic factors (heat and drought) also hits the southern expansion of boreal tree species. Fire and herbivores also help determine the location of the ecotonal areas (areas of mixing of types) of the boreal forests in the north and the temperate forests of the southern latitudes. Thus, under current climatic conditions, the distribution of these major forest groups and the ecotonal areas that separate them approximate a homeostatic condition.

Changing temperature patterns, precipitation patterns, and atmospheric chemistry are expected to affect forest ecosystems throughout most of the United States. The altered climate stressors of most concern are changes in timing, location, and duration of droughts and fall, winter, and spring freeze cycles. The atmospheric changes of importance are the continued increase and eventual doubling of the carbon dioxide concentration in the atmosphere, and alteration of nitrogen and carbon cycles on global scales (Schlesinger 1995).

The impacts from these atmospheric and climatic changes will likely affect relative distribution of forest types; diversity of vascular plants, lichens, and fauna; alteration of growth, regeneration, and mortality patterns of vegetation; altered soil nutrient cycling processes and nutrient pools and increased soil erosion; increased defoliation of tree crowns and increased dieback of fine branches; increased damage to boles and roots from storms, drought, insects, and diseases; heightened outbreaks of native and exotic insects and diseases and increased susceptibility of trees to attack; increased fuel loading and increased alteration of historic fire regimes; and increased deposition of gaseous and particulate air pollutants and increased damage to ozone-susceptible species (USEPA 2000).

## THE FHM AND FIA PROGRAMS

The FHM program uses data from fixed-area plots, aerial and ground surveys, and other monitoring programs like the USFS-FIA and NRI programs, USEPA, NADP, and NOAA to analyze, interpret, and assess the health of all major forest ecosystems in the U.S. Evaluations of forest health arc generally based on the criterion and indicators developed in the Montreal Protocol (Anonymous 199.5). The status and/or change of fragmentation of' forests and land-use patterns, diversity of tree and understory species, the condition of tree crowns, historic and current fire conditions, recent changes from historic drought patterns, air pollution deposition and impacts, native and exotic insects arid pathogens, lichen species richness, and soil cations and pH were evaluated recently as part of a national report on forest health covering 36 States from 1991 lo 1998 (Stolte *et al.* 2001).

In addition to the indicators currently implemented in 36 states, other indicators have been developed and at-c' planned for national deployment including woody debris and fuel loading (2001), and the addition of the structure and diversity of all understory vegetation (2002). All 50 states and territories are planned for annual monitoring by the FHM and FIA programs by 2003. In addition, complementary national monitoring systems with similar data collection protocols are being developed and field tested for urban, riparian, and range ecosystems.

### Landscape Scale Monitoring and Climate Change Models

The FHM and FIA monitoring programs operate on national scales at hundred million acre resolution, and necessitate the development and use of biological, physical, and chemical *indicators* of key processes and components of forest ecosystems that are stable over the sampling window, representative of many forest types, logically feasible, readily interpretable, etc. For example, foliar transparency is am indicator of the amount of leaf area available for photosynthesis, and crown dieback is an indicator of the general functioning of the nutrient cycling system, damage or diseases to the boles and branches of the tree, *etc.* Both indicators work well with a variety of species, change little over the growing season, are readily interpretable, *etc.*

The cost and logistical concerns of monitoring at landscape scales greatly limit the collection of physiological data to support process-level models, such as the carbon-based MAESTRO, BIOMASS, FOREST-BGC and BIOME-BGC, BEX, PnET, LINKAGES, and CENTURY models that estimate gross primary productivity (GPP), net primary productivity (NPP), net ecosystem productivity (NEP), or net ecosystem exchange (NEE) (Landsberg and Gower 1997). However, the FHM and FIA programs do evaluate indicators of growth, mortality, reproduction, foliage, soil chemistry, down woody debris, land use and forest fragmentation, *etc.* at landscape scales that provide some direct *in situ* measurements of primary NEP and facilitate estimation of NPP, NEP, and NEE, provide other landscape scale estimates to validate endpoints of many process models, and provide input for many systems models.

The data collected by the FHM and FIA programs are most useful to forest managers and policy makers concerned with robust, pragmatic models that can be used to inform local politics, and influence economic decisions affecting the flow of timber and non-timber products. Information from empirical models derived from quality-assured, long-term monitoring programs can provide reliable estimates of process model endpoints. The FHM and FIA programs are collecting the empirical data needed for robust, pragmatic models as well as validating the outputs from a variety of process models. The information presented in this report provides a cursory review of some of the empirical data currently being collected by the programs, and some of the results to date.

## CURRENT FOREST CONDITION

The information presented here is primarily from the FHM National Technical Report 1991 to 1998 (Stolte *et al.* 2001) The report includes analyses of data from fixed area plots in 1991 to 1998 (the former FHM Detection Monitoring plots, which are now the Phase 3 plots of the FIA enhanced system), FHM aerial and ground surveys, and other monitoring programs. This information combined with data from other programs provides baseline information to evaluate future conditions of forest ecosystems that have been subjected to changing atmospheres and climates. This paper suggests that relevant FHM and FIA indicators will provide reliable information on many of the biotic and some of the abiotic effects of climate change, how the indicator is related lo forest health, and a brief overview of some of the current forest conditions in the U.S. based on FHM analyses for the period 1991 to 1998.

Some forest ecoregion sections are exhibiting diminished condition (*e.g.*, high mortality volume/growth volume or low soil pH and cations) but in most cases the condition has not been definitively linked to relatively high levels of biotic or abiotic stressors. The results therefore are grouped into three general categories of abiotic stressors, biotic stressors, and current forest condition. Most of the biological data is from the FHM and FIA programs, and most of the abiotic stressor data is from other programs (Stolte *et* al. 2001). GIS maps indicate the status or change in indicators, classes of values based on natural breaks in the data, and the location of forest ecoregion sections (Bailey 1995) that have the relatively high or low values for each indicator. GIS maps were also used to identify ecoregion sections with the highest numbers of stressors and/or relatively diminished indicators of forest condition.

### Biotic Stressors

The FHM National Technical Report 1991 to 1998 (Stolte *et al.* 2001) identified biotic stressors of most concern in U.S. forests. They were exotic insects, diseases, and plants, and unusually severe outbreaks of native insects and diseases responding to favorable changes in forest ecosystems. In most cases there were direct links to current and past human activities.

#### Insects and Diseases

Native insects and diseases (pathogens) are natural components of any healthy for-est ecosystem, and play important roles in the normal successional patterns of' tt-cc species and stands. The impact is exacerbated by past management practices that have resulted in senescent systems without a healthy mix of age classes and seral stages. Exotic insects and diseases are unnatural components of current forest ecosystems and lack the biological and climatic controls that usually keep native insect and disease populations under control and limit the effects on forest ecosys-terns. Consequently, exotic species often cause excessive defoliation and mortality and can alter entire forest ecosystems (FI IP 1999).

Climate change is likely to affect insect and pathogen populations and host plant species because changes in carbon dioxide levels, temperature, cloud cover, and water and nutrient availability all affect plant resilience to stress (Ayres 1993). The effects of climate change on native and exotic species populations in forest ecosystems can only be estimated, but significant increases in defoliation and mortality are likely.

Currently the largest problems in the East arc exotic insects and diseases, and epidemic outbreaks of native insects and diseases. The prospect for invasion of new species anti the expansion of existing exotics is high. Currently gypsy moth, hemlock wooly adelgid, and beech bark disease arc exotic species affecting hundreds of thousands of acres in the Last. Other problem insects and diseases in the East include dogwood anthracnose, butternut canker, fusiform rust, and southern pine beetle.

In the West, native insects such as mountain pine beetle, western spruce bud-worm, and spruce beetle, and parasites such as dwarf mistletoe and root diseases are affecting millions of acres of forests. Native insects and disease populations are at epidemic levels due to alterations of' historic fire cycles and other factors that have changed the structure and successional patterns of forest ecosystems, rendering them more susceptible to attack and providing conditions conducive IO supporting large populations of pests.

Projections of native anti exotic insects and diseases impacts on forest ecosystems in the U.S. are disturbing, with an expected increase in mortality of host tree species by 25% or more over the next 15 years (Plate la*) (FHP 1999). These projections are based on current stand conditions, host tree species, and native and exotic

* Plates appear following page 13 16.

insects and disease populations, and do not take into account any additional changes in changes in carbon dioxide levels, temperature, cloud cover, and water and nutrient availability from climate change. Plans are developing for a second iteration of the insect and disease risk analyses that will consider additional changes in host tree vulnerabilities due to climate change.

### Exotic Plant Species in U.S. Forests

Exotic plants, like exotic insects and diseases, have no natural predators to keep them in check and often, particularly if they are invasive in habit, account for a disproportionate percentage of the abundance of the flora. Once established, exotic plant species flourish in areas that support high native plant diversity. A method for quantifying the diversity of understory species was developed in the FHM program and is planned for implementation in the Phase 3 portion of the FIA program in 2002. Native and exotic species richness (the number of species) is a common way at looking at the relative proportions of plant species (Stolte *et al.* 2001).

Climate change is likely to affect the introduction and spread of exotic plant species by increasing the number of open habitats for colonization, as native plant mortality increases and cover is lost because many native species will be unable to quickly adapt to changing environmental conditions (USEPA 2000; NAST 2000a,b; IPCC 2001). Increases in mortality of both overstory and understory plant species are likely to create ideal habitats for invasive plant species that readily adapt to a broad range of temperature, precipitation, and soil conditions and can reproduce quickly to take advantage of openings in the forest.

Initial pilot tests for monitoring native and exotic understory vegetation found that the percentage of native and exotic plants found on each plot in California, Virginia, and parts of Colorado had a relatively large percentage (6 to 30%) of exotic understory species. In general, high exotic species richness was often found in areas where native species richness was high (Stolte 1997). While this information is of limited use now, it illustrates that value of a nationally standardized database on the distribution and spread of exotic plant species will begin to be available on an annual basis in 2002.

### Abiotic Stressors

The abiotic stressors of most concern in forest ecosystems were fragmentation and change in land use of interior forest stands, changes in historic fire regimes, deviations in average number of moderate-to-severe drought years, and relatively high deposition of wet, dry and gaseous air pollutants (Stolte *et al.* 2001).

### Fragmentation and Land-Use of Eastern Forests

Land use change and fragmentation of forest ecosystems are major threats to forest health because the fragmentation of forests isolates the plant and animal gene pools, rendering populations less resilient to stressors. Additionally, as forest become more fragmented and land use changes from forest to developed uses, edge interactions with other land-use types increases and increase the possibility of introduction of new stressors, and generally renders the forest fragments less resilient to stress (Riitters *et al.* 2000a,b).

Climate change is likely to affect land-use and forest fragmentation patterns, since demographic patterns and human use of energy, water, *etc.* are likely to be altered because of changed climate and weather conditions. The development and spread of human populations has led to the fragmentation of forest ecosystems, increased vulnerability to stressors, and sometime a complete loss of habitats. One of the greatest effects of changing temperature and precipitation will be to change the composition and distribution of forest over large areas. Monitoring changes accurately at landscape scales will be essential to make appropriate management decisions for any mitigation of climate change effects on forest ecosystems (USEPA 2000; NAST 2000a,b; IPCC 2001).

While large contiguous blocks of' forest may ttot be of great importance for human use, except its a recreational and wilderness experience areas, they are important to many wildlife species and to maintain plant genetic diversity within the forest ecosystem. l 'rbanization around population centers continues to fragment the forest ecosystems in proximity Lo and more distant areas, and ( he irtct-case and expansion of roads and other transportation corridors creates new opportunities for development within contiguous forest areas (Riitters *et al.* 2000b)

Recent analyses of eastern U.S. forests has shown that although the area of forest land has increased since the early 1900s and stabilized since the 1930s, there has been a steady decline in the area of' interior forest habitat in the eastern U.S. For example, there is a relatively large and stable amount of forest in the eastern U.S., but it is found in increasingly smaller- patches rather than in large, contiguous units. Figure I b shows the small remaining areas of interior forest in the eastern U.S., based on 30-meter pixils from satellite data in the early 1990s. In most ecoregion sections interior forest accounted for less than half of the total forest (Stolte *et al.* 2001 ).

## Air pollution

Air pollutants are always a concern because they are relatively new selective forces (like exotic species) that have not coevolved with existing forest ecosystems and have great potential to cause serious impacts to forest health and sustainability. Air pollutants impact susceptible species through direct degradation of' the photosynthetic system, availability of nutrient and toxic cations in the soils, and/or effects on the vigor of fine roots (Srttitlt 1974). hit- pollutants often work selectively on sensitive genotypes of susceptible species or key ecosystem processes (e.g., soil nutrient cycling) and lead to direct and indirect impacts on productivity, survival, and diversity of plant communities (Miller 1992). Effects on faunal species can be direct (*e.g.*, fluoride) but most often act indirectly through impacts on host plant communities (Olson et *al.* 1992). Some lichen species are especially sensitive to sulfur and nitrogen deposition (Manning and Feder 1980), anti differences in community composition can be used to identify forest areas with significant pollutant deposition (Stolte *et al.* 1993).

Climate change is expected Lo alter emission and deposition patterns of particulate and gaseous pollutants, due to direct effects of changes in wind and precipitation patterns, and indirectly through changes in human use of energy and population demographics (USEPA 2000; NAST 2000a,b; IPCC 200 1). Climate change may increase pollutant emissions, depositions, and exposures in currently polluted areas, and may result in the introduction of air pollutants in areas whet-e current air quality is relatively pristine.

There were large areas of the northcentral and northeastern U.S. that annually received relatively high deposition of nitrogen (nitrate, ammonium, total N), anions (sulfates, nitrates),, and acidic precipitation pH (< 4.5 pH) (Stoltc *et al.* 2001). Aver-age wet deposition of sulfates, nitrates, ammonium, and acidic- precipitation were elevated in millions of acres of forests in the Easter-n U.S., primarily in the eastern Great Lakes area, the Northeast, and the mid-Atlantic. Interpolation of' deposition from 1979 to 1995 indicated that elevated nitrate, ammonium, and total nitrogen affected all or most of 19, 48, and 25 ecoregion sections, rcspcclively, our of a total of 109 forested ecoregion sections in the U.S. Elevated sulfate deposition affected all or most of 27 of' 109 ecoregions in the U.S. Relatively low acidic precipitation affected all or most of 59 of the 109 ecoregion sections. The biological ramifications of this deposition are currently under evaluation.

Climate change is likely to affect the severity and distribution of ozone exposures, and the relative impacts to plants, since emission patterns of nitrogen oxides and temperature, amount of-solar radiation, and wind patterns are likely to affect ozone formation and transport, as well as changes in soil moisture patterns that will affect plant uptake of ozone (USEPA 2000).

An evaluation of average ozone concentrations for the period 1993 to 1996 indicated many forested ecoregion sections in the East and parts of California in the West experienced elevated ozone exposures. Ozone exposures wet-e **frequently** high enough to injure ozone-susceptible plant species identified in laboratory and field studies (Miller *et* al. 1992). In the East, ozone injury on ozone-susceptible hioindicator species in 1994 to 1998 was consistently found in parts of the South, the Mid-Atlantic area, New England, and parts of the eastern Great Lakes area. The amouttt of injury found was considered slight-to-moderate in many of tho affected areas, and severe in some parts of the Mid-Atlantic (Stoltc *et* al. 2001).

**Number of Moderate-to-Severe Drought Years**

Climate change is expected IO shift the location and severity of droughts in many parts of the U.S. Changes in temperature, rainfall amounts and titning, and plant evapotranspiration will probably alter the historic drought patterns in the Intermountain West, Northeast, and Southeast U.S. (Kareiva *et* al. 1993). Moderate-to-severe droughts are not a new stressor and have coevolved with forest ecosystems. Deviations in historical patterns of drought, in combination with other factors such as exotic insects and pathogens, high fuel loading, *etc.*, are a serious concern because of' the possibility of exacerbating normal patterns of growth, tnortality, fit-e, and insect and pathogen predation (Mattson and Haack 1987). Drought patterns were analyzed using Palmer Drought Severity Index data from 1895 to 1998 (Stolte *et al.* 200 I )

Annual drought from 189.5 IO 1998 indicated a cyclic pattern of moderate-to-severe droughts affecting 40% or more of the U.S. on an average of 26 years, and an average shorter 13 year cycle affecting 20 to 30% of the U.S. (Stolte *et* al. 200 1). Additional analyses indicated I hat the average number of moderate-to-severe drought years in any 10-year period from 1895 to 1998 ranged from one in many ecoregion sections to three in the Northern Unglaciated Allegheny Plateau section. The deviation in number of years of moderate-to-severe drought from 1989 to 1998 indicated that ecoregion sections in the Rocky Mountains and the Southwest had two or more additional years of drought, while most of the East was wetter than the historical average. The drought conditions in these areas may have contributed to the high insect and pathogen defoliation and mortality in these areas (FHP 1999) and increased fire risk in these areas (FSL 1999a).

**Alteration of Historic Fire Regimes**

Fire has been a powerful, selective regulatory mechanism in forest ecosystems for many millennia. It is a natural part of the environment, and fire-affected ecosystems have depended on particular frequencies and intensities of fires. For these ecosystems to remain in their natural successional patterns the historic fire regimes they have adapted to must be present. Humans have altered historic fire regimes through fire suppression, tree harvesting, and prescribed burning. Influencing either the frequency or intensity of fire may change the species composition and age structure of a fire-adapted community, as well as physical and chemical soil characteristics (Kimmins 1987).

The historic fire regimes were based on the frequency and intensity of' burning, which depended on the buildup of fuels, weather conditions, and the occurrence of ignition sources. Historically, most fires were started by lightning strikes, and fires burned until they ran ottl of fuel, were stopped by natural landscape features, or- were doused by significant precipitation events. Changes irt historic fit-c regimes and other land management practices have resulted in epidemics of native insects and pathogens, relatively higtt mortality for some species, and general shift from historic cycles of nutrient cycling and seral development of stands (FSL 1999a)

Climate change might further modify historic fire conditions, and/or lead to an increase or decrease in fire severity and acres burned. Alterations in fuel loading are likely because of' the anticipated increases in tree mortality from drought or flooding, increased insect and pathogens, and/or changes in understory vegetation. In addition, changes in drought patterns may alter fire weather conditions fi-otn historic fire regimes (USEPA 2000).

The three current condition classes categorize departure from the historic fire regimes based on five ecosystem attributes: disturbance regimes, disturbance agents, smoke production, hydrologic function, and vegetative attributes. Condition class 1 indicates current ecological conditions are similar to historic conditions, and little or no management action would be needed for restoration. Condition class 2 is characterized by moderate deviations in ecological conditions compatible with historic fire regimes, and restoration to historic fire regimes requires sonic silvicultural treatment. Current condition class 3 represents major deviations fi-otn the ecological conditions compatible with historic fire regimes, and significant management activities such as harvesting and replanting lo restore the historic- fire regime (FSL 1999b).

Forty-to-seventy percent of forests, mostly in the West, southern Lake States area, Northeast, and parts of the South, would need moderate-to-extreme management activities to return the forest to their historic fire regimes (Plate 2a*) (Stolte *et al.* 2001). One hundred percent of some forest types (*e.g.*, redwood forests, red-white-jack pine, western white pine) need management action to restore them to historic conditions, while other forest types (*e.g.*, oak-gum-cypress, longleaf-slash pine) are in historic fire regime condition and need little or no restorative management actions.

The FHM and FIA programs have collaborated on the modification of methods for collecting data for fire behavior and risk models, and national implementation of this indicator started in summer of 2001. This monitoring will provide annual standardized monitoring of both coarse and fine down woody debris and other fuel loading variables, as well as other data on factors that affect current fire regimes.

## Forest Condition Indicators

Condition indicators are basically the physical, chemical, and biological responses of the forests to the myriad biotic and abiotic factors that shape each ecosystem. They may be broadly defined as metrics that provide quantitative or qualitative estimation of the current state of one or more key ecosystem components or processes that are important in the overall integrity of the system. Therefore, multiple condition indicators contribute to improved understanding of the general functioning of forest ecosystems. Long-term monitoring of' conditiort indicators provides estimates of the changes in forest ecosystems over time.

Condition indicators analyzed to date include estimates of species richness (trees, understory, and lichens), productivity (growth), forest structure (size, distribution, *etc.*), tree crowns (status and change in dieback and foliar transparency), insect and diseases (defoliation and mortality), mortality (lost volume/gained volume), soils (pH, carbon, nitrogen, and nutrients), tree damages (insects, diseases, storms, *etc.*), and sequestration of carbon in trees and soils (litter, O-horizon, and 0 to 10 and 10 to 20 cm mineral samples). Not all of these condition indicators are addressed in this report.

## Diversity of Trees, Understory Plants, and Lichen Species

The diversity of plant life often is correlated to the aesthetic value of a forest system, stability of a system, and diversity of insect and animal life possible. Areas of high plant diversity provide food and habitat for a relatively high number of faunal species. The diversity of plant life, often measured as the number of plant species or species richness and some measure of abundance, such as cover, is primarily dependent on four factors — climate, soils, topography, and the type and amount of disturbance. Forest stands in areas of natural disturbances, warm and wet climates, stable and nutrient rich soils, and diverse topography typically contain the highest number of plant and animal species.

The number of species is only relevant within a given ecological area, and change in species richness and abundance, and the nature of the change, are most relevant. Of concern is the displacement of native plant and animal species by exotic and invasive noxious species. Exotic plants can account for 30% or more of the flora in natural forest stands and often represent a disproportionate percentage of the overall plant coverage (Stolte 1997; Stolte *et al.* 2001).

Climate change is likely to affect the diversity of many vascular and epiphytic plant groups, since many of the prime determinants of species composition (carbon dioxide concentrations, temperature, relative humidity, precipitation, storms, *etc.*) are expected to change over large areas of the U.S. (USEPA 2000; NAST 2000; IPCC 2001).

The diversity of tree species in the 36 States evaluated varied geographically, with relatively high diversity (21 to 28 species) itt the East and much lower tiivcrsity (1 to 5 species) common in the West (Stolte *et al.* 2001). These differences in number of' tree species reflect the differences in moisture regimes, soils, topography, disturbance history, *etc.* Tree species diversity, and change in diversity, will be available at finer spatial scales (1 plot every 6000 acres) as Phase 2 of the FIA program becomes fully implemented, and combined with aerial surveys and satellite monitoring will he able to detect changes in species presence and abundance.

The diversity of' understory plant species, measured in FHM pilot tests in a few states, was relatively high (2 to 20 species) in most areas except parts of the Georgia and Alabama (Stolte *et* al. 2001), which may reflect the large amount of' forest area devoted to tree plantations and other land management activities. This indicator will begin to collect nationally standardized data on all vascular plant species, including species identification and cover, and wilt also be an invaluable monitoring tool to detect changes in species distributions due to climate change effects.

Lichen species richness is a good indicator of air quality and microhabitat climatic conditions (Stolte *et al.* 1993; McCune *et al.* 1997). Average lichen species richness was relatively high (11.5 to 19.8 species) in ecoregion sections in the Northwest, eastern Great Lakes, northern New England, and parts of the Southeast (Stolte *et al.* 2001). Relatively low average diversity (2 to 9 species) was found in the Interior West, interior California, southern New England, western Great Lakes, and parts of the Southeast. Relatively low lichen species richness was expected in the drier, tree-sparse regions of the West, but the relatively low diversity in the mesic forested areas of the East was unexpected.

Lichen species diversity may be one of the first groups of plant to respond to changing climatic conditions. Since lichens lack stomata and cannot control gas exchange, changes in lichen communities may be the first to respond to temperature and moisture changes. This might be especially evident in stands where no other significant disturbances are occurring. Analyses of' lichen community data relates sensitivity of lichen species to known air pollution and climatic gradients, and each plot is given an air pollution and climate score. The baseline climatic scores for many states are already established, and can be obtained for many others after development of appropriate gradient models (McCune *et al.* 1997)

**Dieback and Transparency of Tree Crowns**

Tree crown condition is an important indicator of individual tree and forest stand health. A large number of studies have related crown condition to tree growth and productivity for it variety of trees species. Generally, trees with large, full crowns have the potential to maximize gross photosynthesis because they are able to capture a large portion of the solar radiation available during the growing season (Stolte 1997). Two crown variables frequently reported on are the mortality of the terminal twigs in the sun-exposed portions of tree crowns (diehack) and thr transparency of the foliage of' the whole tree crown to sunlight (i.e., sparseness of the crown foliage). These variables generally relate to the amount and fullness of foliage, and vigor of the apical growing points of the crown (Stolte *et* al. 2001).

Climate change is likely to affect tree crown condition. Changes in temperature and precipitation patterns, insect and pathogen activity, and nutrient cycling patterns arc all likely to affect the size and amount of foliage in tree crowns, and the vigor of the apical growing twigs on the crowns.

The status and change in crown transparency and dieback of hardwood and softwood species indicated that many ecoregion sections in the Great Lakes, some in the Northeast, and parts of the West had relatively diminished crown condition (relatively high foliar transparency and high crown dieback), based on the condition of tree crowns on other plots (Stolte *et al.* 2001 ). This condition could often be attributed to insects and pathogens, current climatic conditions, or stand conditions. In some ccoregion sections, further evaluations were needed to determine the associated cause of the diminished crown condition.

The current condition (1998) and recent changes in hardwood foliar transparency found in ecoregion sections in the Great Lakes area were relatively high, with current averages of 20% or greater, and an overall increase from 1994 to 1998 of 2% or more per year. The current condition (1998) and recent changes in hardwood crown dieback was also high in the Great Lakes area, and in ecoregion sections in New England and northern Idaho.

The current condition (1998) and recent. changes in softwood foliar transparency found in many ecoregion sections in the Great Lakes, the West Coast, parts of the mid-Atlantic, and much of the Southeast were relatively high, with current averages of 15% or more (Plate 2b*), and had increased 0 to 2% or more per year. The status of clieback in softwoods showed tnany of the same ecoregion sections in the Great Lakes, Northeast, parts of the South, and parts of t he West had relatively high dieback levels (4.6 to 19%), particularly along the Maine coast. Most of these same areas showed dieback to be increasing at 0 to 2% or more per year.

## Biotic and Abiotic Damage to Trees

Damage caused by pathogens, insects, storms, and human activities can significantly affect the growth, reproduction, and mortality of trees. A damage severity index was calculated based on the number of damages recorded on the tree, their location, and their severity (Stolte *et al.* 2001). Damage indices were calculated for individual trees and averaged at the plot level for softwoods and hardwoods.

in the field, tree damage is recorded if it is considered serious enough to increase the probability that a tree will be infected by lethal pathogens (such its open wounds or broken branches), that a tree will die pretnatureiy (presence of pathogenic conks, cankers, or broken roots), or that the growth and/or reproduction of the tree wilt be seriously depressed (such as high defoliation or broken branches).

Climate change is likely to affect the severity and spatial patterns of damage to trees, since tree damage is a combination of many biotic (insects and diseases) and abiotic factors (wind storms, changes in spring and fall freezes, *etc.*) that would be affected by a changing climate (USEPA 2000; NAST 2000a,b; IPCC 2001 ). Types of tree damage that are likely to be affected by climate change include storm damage to crowns, boles, and roots, defoliation from weather or insects and pathogens, and damages to tree bole from pathogens.

The damage found on hardwood and softwood trees, from multiple and unidentified sources, that were likely to affect the growth or survival of the trees were evaluated as another factor in tree and forest ecosystem health and sustainability. Trees in the West were found to have more damage than trees in the East (Stolte *et al.* 2001). The causal agents of the damage are still under evaluation.

Hardwood tree damage was relatively high (an average of' 40 to 100% of' trees injured) in parts of Colorado, western Wyoming, Idaho,and California. In contrast, most of the eastern ecoregion sections had only 20% or less of trees with any damage recorded. The same general pattern held for softwood tree damage, with most Western ecoregion sections averaging 30 to 100% of' the trees damaged, and most Eastern sections with 10% or less trees damaged. In some Eastern sections, averages were higher (10 to 30%) In all areas, for both hardwood and softwood species, individual plot-level damage severity indices were sometimes relatively high (57 lo ] 60 index valttc).

## Tree Mortality

The loss of tree volume due to mortality is a natural part of any forest ecosystem. The annual mortality, in terms of wood volume per acre, was based on the trees that have died since plot establishment. Different forest types grow under very different conditions grow at different rates, so a simple measure of mortality volume is not a good measure of forest health. That is, a greater tree volume may be lost to mortality in a healthy forest in the southeast than the total standing volume of some dry western forests.

A useful mortality indicator for forest across the U.S. is to ratio annual mortality volume to gross volume growth (MRATIO). Trees lost to harvest are not included in mortality estimates. An MRATIO value greater than one. indicated that mortality exceeded growth and live standing volume had actually decreased. In addition, the dbh (diameter at breast height) of trees that died compared to the dbh of trees that are still living at the plot (DDLD ratio) gave an indication as to the relative size of the trees lost to mortality. A DDLD greater than l indicates that the average size of the trees that died was greater than the average size of' the remaining live trees.

Climate change is likely to affect tree mortality patterns since many tree species will be in areas where the changed climate no longer supports the trees that were found there historically. Large areas of' tree mortality are likely, particularly along ecotonal areas between major forest types. In addition, the myriad of other stressors that are likely to change, such as insect and disease activity, will further increase mortality in some areas (Iverson *et al.* 1999).

MRATIO values wet-c relatively high (0.6 to 10) in the western Great Lakes area, northern New England, and parts of Idaho and northern California (Stolte *et al.* 2001 ). On some plots in these ecoregion sections with high MRATIOs, the DDLD values ranged from 1 .2 to 10, indicating the trees that died were on average the largest trees in the stand. Some of the mortality can be attributed to current stand conditions, insect and disease activity, and other factors, and some mortality causes are still under evaluation.

Forest soils are a critical component of any healthy and sustainable forest ecosystem. When soil processes are significantly disturbed, the viability of the whole ecosystem is affected. FHM investigated the total C and N, pH, and nutrient cations (K, Ca, and Mg) of the top 50 cm of soil on FHM plots. Often this included the litter layer, the O-horizon if present, and the A-horizon. Litter and soil samples were collected at the surface, 0 to 10cm, and 10 to 20 cm depths and shipped to a lab for processing and analysis. In addition, soil erosion and compaction measurements were made. Since soil measurements have only recently been implemented nationally only plot-level averages, and not ecoregion section averages, are discussed (Stolte *et al.* 2001).

Climate change is likely to affect decomposition processes and nutrient availability through alteration of soil moisture, soil temperature, arid litter quality. In addition, changes in the timing and amount of rainfall may affect the severity and patterns of soil erosion. As temperature and precipitation changes, short and long-term changes in tttineral nitrogen availability due to increased C:N ratios nitrogen will occur (Ayres 1993).

Nutrient cation availability was low on many plots in the Eastern states (Stolte *et al.* 2001 Exchangeable calcium ranged from 0 to 1.0 on some Eastern plots, and ranged from 1.0 to 50% on many Western plots and scattered plots in the East. Exchangeable magnesium values ranged from 0.04 to 0.9% on many Eastern plots, anti on many mountainous plots in California, Oregon. Washington, and Idaho. Magnesium values of 3 to 18.5% wet-e found on only a fttw plots in the West. Mineral soil samples are analyzed for exchangeable calcium, magnesium, and other cations by ammonium acetate extraction at pH 7.

The pH of the surface soils, measured by water extraction, was relatively low (3.1 to 4.5) on many plots in the Great Lakes area, the Northeast, the mid-Atlantic, and the South. In the West, soil pH values were almost always higher, ranging from 4.5 lo 8.2 that is probably attributed to the more calcareous soils found in arid regions of the West. A few plots in Oregon, Washington, Idaho, and Wyoming had lower pH values of 3.5 lo 4.5. Whether the relatively low pH values of soils in the East are to be expected is currently under evaluation.

Essential data on soil nutrients, pH, carbon, nitrogen, erosion, and compaction will be available annually to detect climate change effects as this indicator is fully implemented, and results of chemical analyses become available.

## Carbon Sequestration

The amount of carbon sequestered or lost in forest ecosystems is important since forests are large sources or sinks of carbon depending on conditions. Carbon sequestered in wood volume was evaluated using procedures developed by the USFS's Global Change program (Stolte *et al.* 2001). It estimates the amount of volume added to both above and below tree components and subtracts the amount of volume lost to mortality and harvest, with the mortality volume weighted higher than harvest volume because finished wood will take longer to be returned to the atmosphere as carbon.

Climate change is likely to affect carbon sequestration patterns in many parts of the U.S. Since the primary factors in car-bon sequestration by trees arr the amount of photosynthetic substrate available and the rates of net photosynthesis realized. Available leaf area and amount of net photosynthesis are affected by changes in precipitation, temperature, and radiation patterns that are altered by climate change. The amount of carbon fixed will increase in some areas and decrease in others. Increased mortality due to altered drought, insects and pathogens, and other factors will release additional carbon back into the atmosphere (Schlesinger 1995; USEPA 2000; NAST 2000a,b; IPCC 200 I ) .

The annual periodic change in carbon sequestered as lbs/ac/yr was highest in the Pacific Northwest (2.501 to 4050 lbs/ac/yr) and also high in most other ccoregion sections in the U.S. The only ecoregion sections showing a loss of carbon were in parts of southern Idaho, eastern Oregon, and western Colorado (-499 to 500 lbs/ac/yr) (Stolte *et al.* 2001).

## Tally of Condition and Stressor Indicators by Ecoregion Section

In an initial step to examine the current condition and potential risk to forest ecosystems from relatively high biotic and abiotic stressors, a tally of three types of indicators (condition, biotic stressors, abiotic stressors) was done at the ecoregion section scale. The number of condition and stressor indicators, out of a total of 20 common to each ecoregion section, with relatively high or low values (*e.g.*, high dieback or low carbon sequestered) was tallied for each ecoregion section.

While this simple analysis only identified ecoregion sections where relatively high numbers of assorted stressor and condition indicators were found, the intersection of these ccoregion sections with areas of expected climate change will identify ecoregion sections where changing climate conditions are interacting with other factors already present in the forest. Conversely, climate change in areas where current stressor and condition indicators are in relatively better condition may provide areas where the *in situ* impacts of‘ climate change may be more clearly associated with future changes in forest condition.

The status and change of transparency and dieback of hardwoods; status and change of transparency and dieback of softwoods; mortality/growth volume ratio; carbon sequestration; hardwood damage; and softwood damage were the condition indicators tallied. Deposition of sulfur, precipitation pH, ammotiium, nitrate, hydrogen ion deposition, ozone exposure, drought, and change in historic fire regimes to a curt-t-nt fire condition Class 3 rating in 40% of any ecoregion section were the abiotic and biotic stressor indicators tallied.

Indicators were considered to be in a relatively *poor* or *undesirable* condition if thry were in the lowest (*e.g.*, carbon sequestered) or highest (*e.g.*, mortality ratio) classes of values, based on natural breaks in GIS mapping. For evaluation of‘ the change in historic fire regimes indicator, ecoregion provinces and associated sections with greater than 40% of the forested area in current condition Class 3 (greatest amount of land management needed to restore it to its historical fire regime) in 40% or more of the ecoregion section was considered the poorest condition. For evaluation of the drought indicator, the range of values observed was broken into 6 classes, and classes 5 and 6 (the most number of years deviation from historic 10-year averages) were considered the poorest. Hardwood and softwood damage indicators were put on the same scale so damage greater than 30% was considered the poorest.

The ecoregion sections Southern Superior Highlands, Green, Taconic, and Berkshire Mountains, and the Northern Ridge and Valley sections had the highest number (9 to 10 of the 20 indicators) in the least-desirable categories (Stolte *et al.* 2001). Other areas with relatively high numbers of' indicators in the least-desirable classes (5 to 10 of the 20 indicators) were the Great Lakes, Northeast, mid-Atlantic, and parts of Idaho and southern California.

## DISCUSSION

The integrated FI IM and FIA programs provide a comprehensive biological monitor-ing system that is spatially and temporally robust and ecologically diverse. These monitoring systems will collect data on key indicators of' forest ecosystem processes that will be important in developing and refining empirical models, and validating process models such as PnET, *etc.* These monitoring systems **are** likely to detect many of' the probable biological, physical, and **chemical** changes in forest ecosystems that are associated with climate change. The difficulty will be to tease out the effects caused by climate change from changes due to myriad other biotic and abiotic fac tors.

Process models arc always very important IO estimate future condition of forests based on current condition and stressors, current condition, suggest areas where management actions might improve forest health, and estimate probable outcomes of **any** proposed management actions. The integrated FHM and FIA long-term national monitoring systems utilize landscape-scale indicator monitoring and water-shed-scale, intensive site process monitoring systems. The integration of the land-scape scale **anti process** scale data to produce the most useful intormation on **forest** health and sustainability is one of the biggest challenges facing scientists today. I Iowever, the opportunity is there since the FHM and FIA monitoring programs arc operational, and when all components arc fully implemented will provide much of the basic information necessary for land managers and policy makers to protect and improve forest health in the United States.

The data needed for these models (water relations, C-allocation, *etc.*) is short-stcp, intensive process monitoring conducted over decades by a relatively few government, academic, industrial, and private research **groups**. In the USFS, this work is found primarily at Long-Term Ecosystem Research sites, Experimental Forests, Research Natural Areas, other National Forest Systems lands, and National Resource Conservation Service sites. A plan for a national integrated process-level is being developed as part of FHM's Intensive Site Ecosystem Monitoring program. The ISEM component of FHM is based on guidelines for selection of sites, biotic and abiotic **c-ore** processes monitoring, etc. (Stolte 1997).

The effectiveness of the combined FHM and FIA programs to detect and inter-pret changes to forest ecosystems from climate change could be improved by increasing the breadth and intensity of' monitoring in ecotonal **areas that** are sensitive to changing conditions, in other areas in forest containing susceptible components or processes, other forest-related systems such as urban, riparian, and range ecosystems, and generally in forested areas where changes in climate and weather are expected to be the greatest. Additionally these monitoring systems would be improved by the inclusion of new indicators, including such major ecosystem components such as key insects, amphibian, and fauna species that are not directly represented in the current sampling and analyses protocols.

One of the biggest challenges will be to tease out the effects of climate change from other biotic and abiotic stressors impacting forests. Some analytical approaches that might be initially attempted are to: (1) Identify exact components (*e.g.*, individual species, *etc.*) and processes (*e.g.*, growth, mortality, *etc.*) that are most sensitive to climate change (*i.e.*, climate change indicators); (2) Evaluate suites of climate change indicators using multivariate and other sophisticated analytical techniques. (3) Use spatially based approaches of stratifying analyses where the condition of the forests is relatively good now (based on current FHM and FIA indicators), there are few stressors affecting forests, and significant changes in climate are expected.

The baseline conditions established by the FHM and FIA programs have identified forest ecosystems that are already showing relative differences in a variety of forest indicators, many of which are relevant climate change indicators. For many of these indicators there were statistically significant changes in condition (positive or negative) within the last 10 years. These forest ecosystems have relatively high probabilities of continued responses to current biotic and abiotic stressors. The additional stress added by changing climate scenarios and impacts to forests in the future may be possible to delineate because the FHM and FIA programs have provided the essential baseline information to tease out climate change effects from other stressors.

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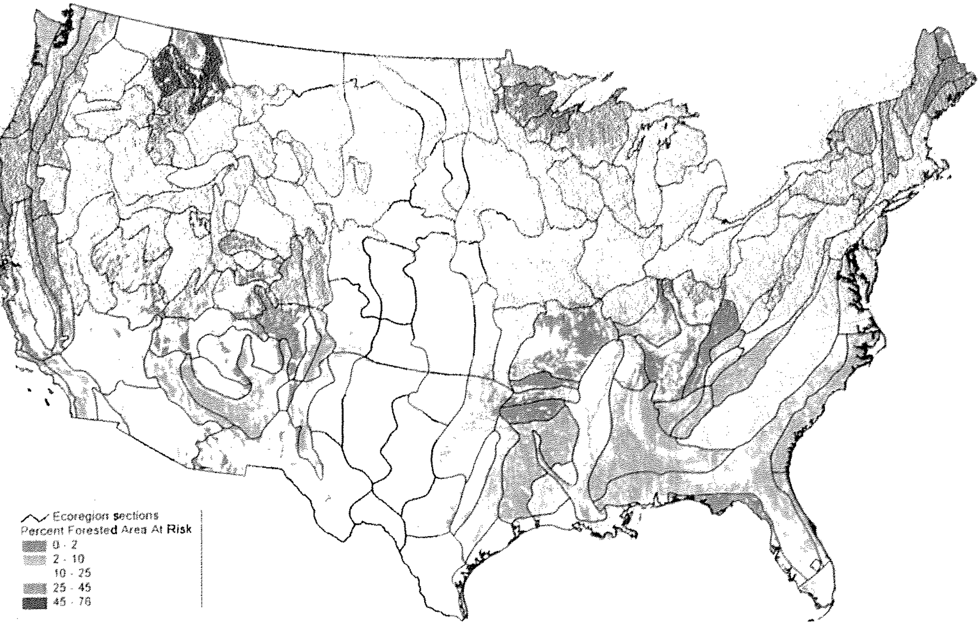
A




B

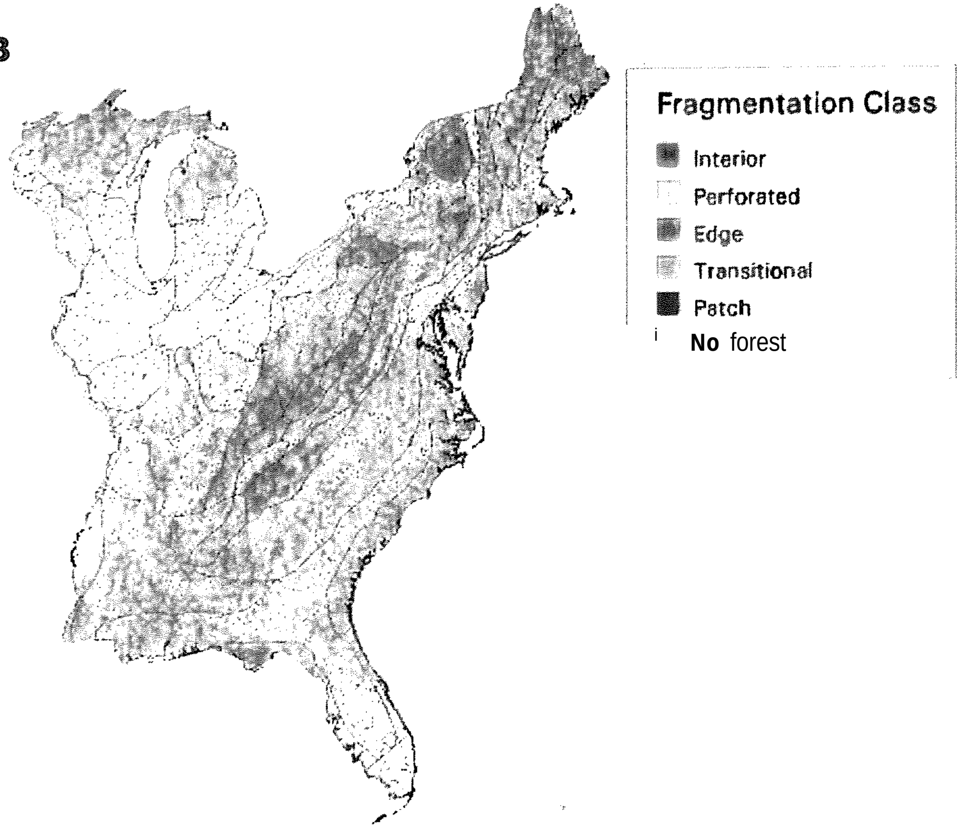
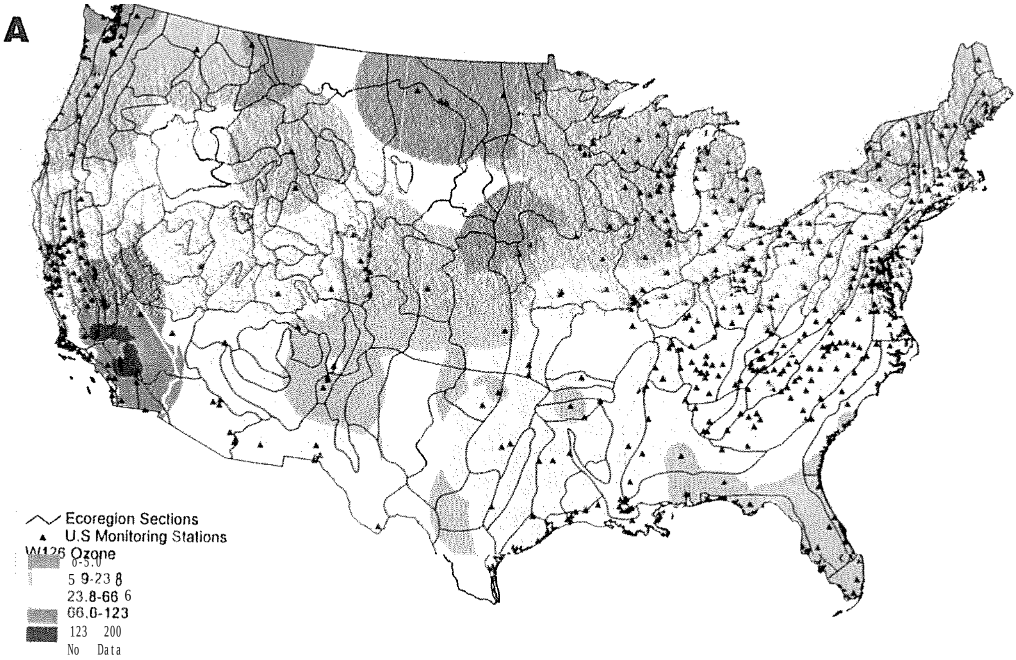



**PLATE 1A. The percent of forest areas in each ecoregion section at risk for elevated mortality of host species from insects and pathogens.** Mortality of host species in these areas is expected to increase by 25% or more over the next 15 years. **B. Fragmentation of forests in the Eastern U.S. based on satellite data from early 1990s.**



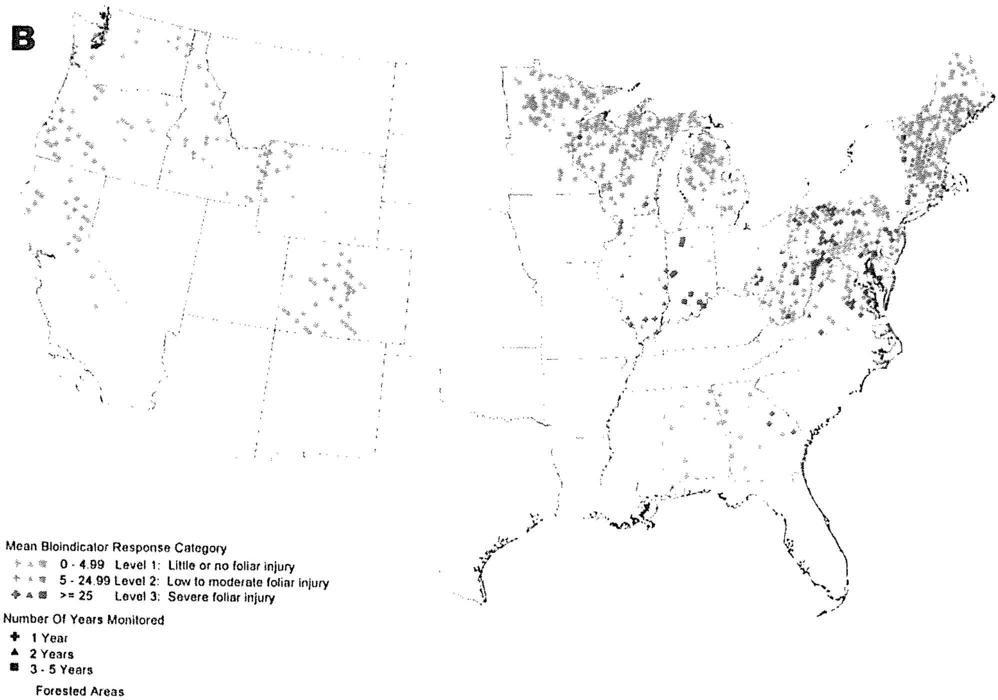




**FIGURE 2A. The distribution of the W126 ozone indices average for the period 1993-1996.** The classes of indices values are based on levels suspected of injuring susceptible to resistance Eastern tree species. Lowest values are capable of injuring most susceptible species; highest values are capable of causing injury on all susceptible species. **B. The mean Ozone Injury index is based on the number of leaves with foliar ozone injury, the severity of the injury, the number of plants injured, and the number of bioindicator species with injury at the monitoring site for the number of years indicated (1994-1998) by different symbols.** Higher levels indicate more severe injury on more plants of more species.

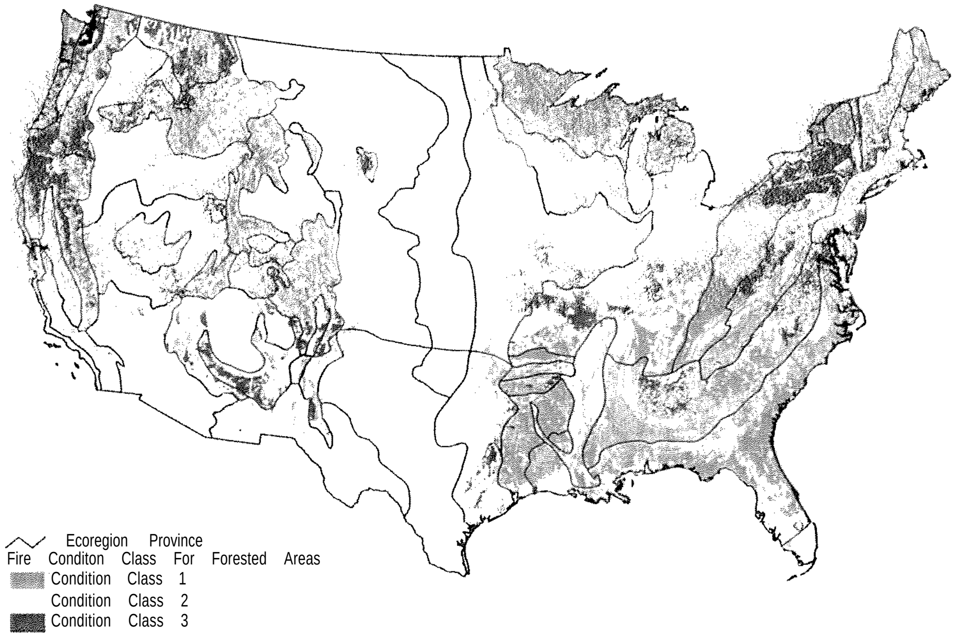




**FIGURE 3A. The current condition class of forested ecoregion provinces relative to historic fire regimes.** Condition class 1 means that ecological conditions today are similar to those in historic fire regimes. Condition class 2 means ecological conditions are different from historic fire regimes and some silvicultural management action would be necessary to restore to historic fire regimes. Condition class 3 means that ecological conditions are significantly different from historic regimes and intensive management actions would be required to restore historic fire regimes. **B. The average percent foliar transparency of softwood tree crowns in ecoregion sections (colored polygons) in 1998. The closed circles show the average transparency of softwood tree crowns at each FHM plot in 1998.** The ecoregion section averages are derived from the plot values within each ecoregion section.

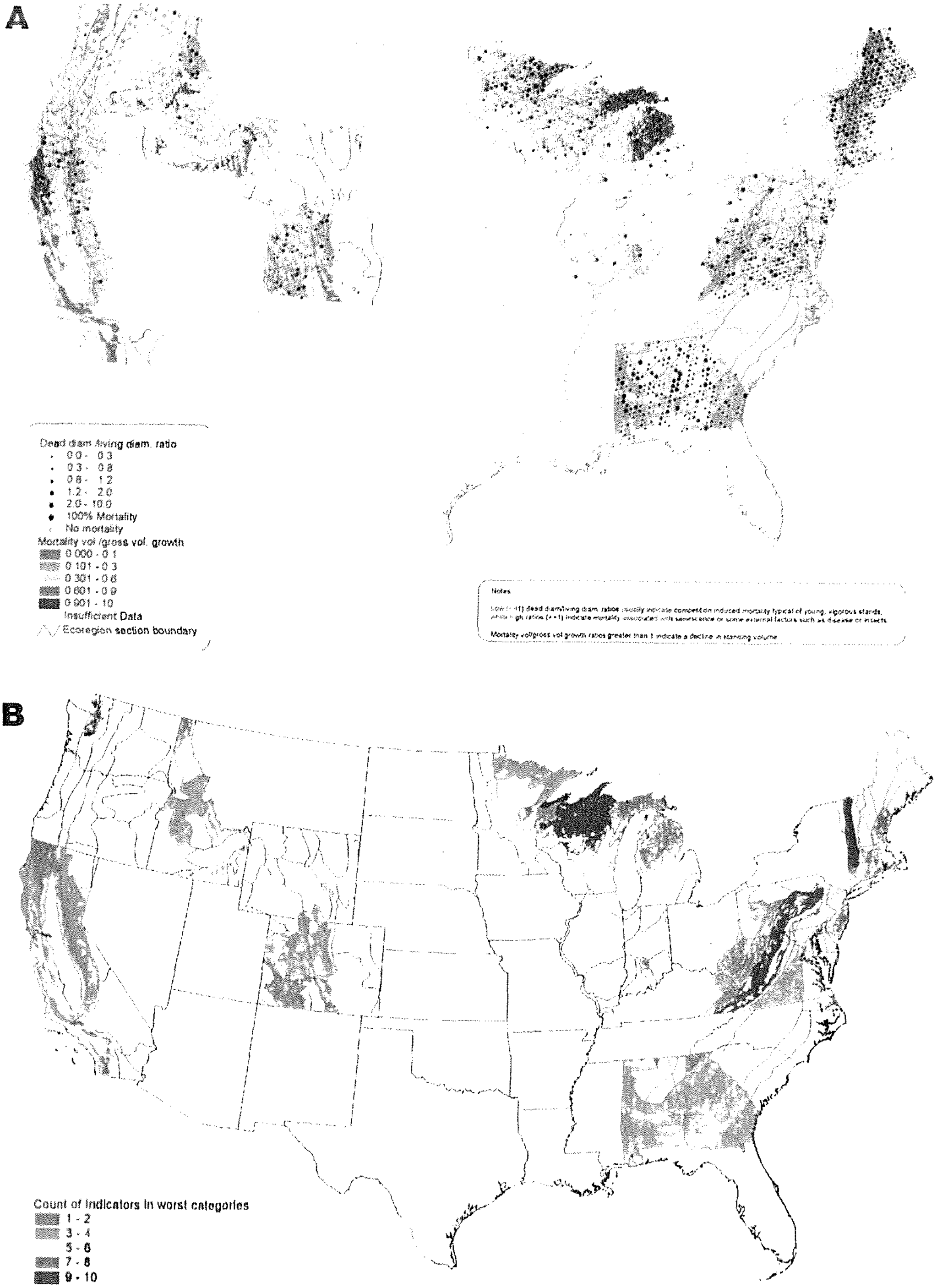



**FIGURE 4A. Mortality of trees expressed as the mortality volume over growth volume (MRATIO).** Polygons (colored) indicate average MRATIO values and filled circles indicate average diameter of trees. MRATIO values exceeding 1 indicate that more volume was lost to mortality than was gained in growth over the period of record. DBH values exceeding 1 indicate that the average size of trees lost to mortality was greater than the average size of trees remaining. **B. The number of indicators (out of a total 20) in the highest or lowest 2 classes in each ecoregion section (highest or lowest classes based on the nature of the indicator, e.g., high dieback or low soil pH).** The classes are the same used in generating GIS maps of spatial patterns of the indicator.